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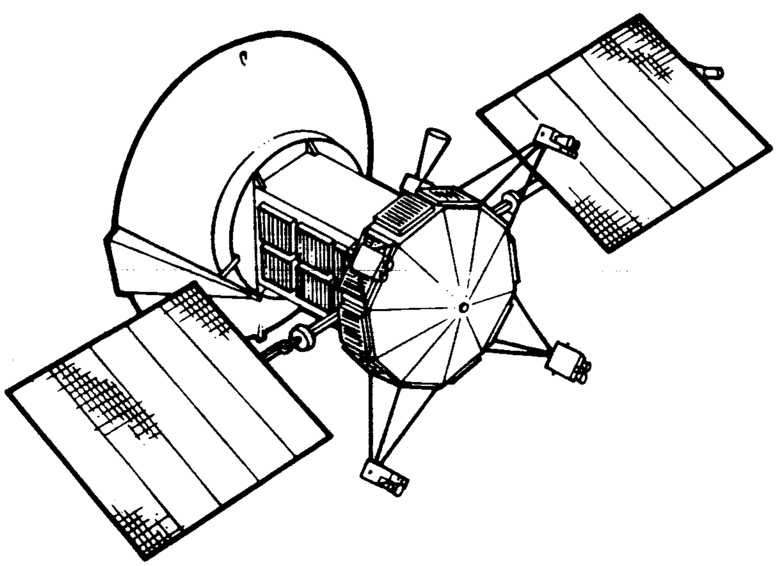
V-GRAM

Magellan Quarterly Bulletin About Venus and the Radar Mapping Mission



OCTOBER 1986

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

V-GRAM

Issue No. 9 October 1986

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MAGELLAN UPDATE

Neil L. Nickle
Magellan Science Manager

Launch Date Rescheduled

The Magellan Project has been rescheduled to an April 25, 1989 launch, 12 months beyond the previous launch date. As a result, a major replan of the Project was initiated to accommodate a new budget, a new mission design, and new delivery schedules. Other upper-stage alternatives are also being considered because of NASA's cancellation of the Shuttle/Centaur upper stage. Specific studies include performance, schedule risk, technical risk, and procurement considerations. One attractive alternative to the Shuttle/Centaur is the Shuttle/Inertial Upper Stage--a dual, solid-propulsion rocket that utilizes a longer trajectory than the Centaur configuration. A Type IV trajectory, one that requires a heliocentric transfer angle of more than 540 degrees, extends the flight time to Venus by almost a year. Solar conjunction will interrupt the mapping phase for 15 days early in the primary mission, creating a 27-degree longitudinal gap in mapping coverage.

Impacts of a Delayed Launch

There are good and bad aspects associated with any schedule slip. The bad aspects for the Magellan Project include increased costs and a concern with maintaining interest and support of our science investigators. Although we do not anticipate problems, special efforts will be made to assure high interest by conducting data-interpretation workshops, and by sponsoring science meetings and activities related to the establishment of a complete data base of existing Venus data. Our strategy is to make the best of the situation by being prepared to make better use of the Magellan data during the mission. Through the media of the "V-Gram", public seminars, and film and slide presentations, we will strive to keep the general public informed about the role of Venus exploration in understanding the solar system. The science investigators have indicated that their interests remain undaunted, and that this delay will provide an added opportunity of using the Soviet Venera 15 and 16 data sets in preparation for the wealth of Magellan high-resolution imaging, altimetry, and radiometry data.

Cooperation with the USSR

Through the efforts of Professor James W. Head of Brown University, a Magellan investigator, and scientists of the Vernadsky Institute, USSR, international symposia have been held for the exchange of scientific views about Venus. The first and third meetings were held at Brown University; the second meeting was in Moscow. Future meetings will be held at one of those two locations. N. Armand, V. Barsukov, A. Basilevsky, A. Bogomolov, I. Chernaya, B. Ivanov, I. Kodakovsky, M. Kronrod, V. Kryuchkov, M. Markov, L. Mukhin, V. Myasnikov, O. Nikolaeva, A. Pronin, O. Rzhiga, A. Sukhanov, Y. Surkov, Yu. Tyuflin, and V. Zharkov of the Soviet Union have presented preliminary scientific results of the Venera 15 and 16 missions, a description of the missions, and a description of the radar systems used. The Soviets also presented the Magellan Project with Venera data tapes consisting of processed synthetic-aperture radar (SAR) digital data for use by the Project for planning purposes. A request was made to not use the data for scientific purposes until the information is published by the Soviets, which is expected sometime this year. The symposia are mutually beneficial to the US and to the USSR in the exchange of scientific information, and in the discussions about future plans for planetary exploration.

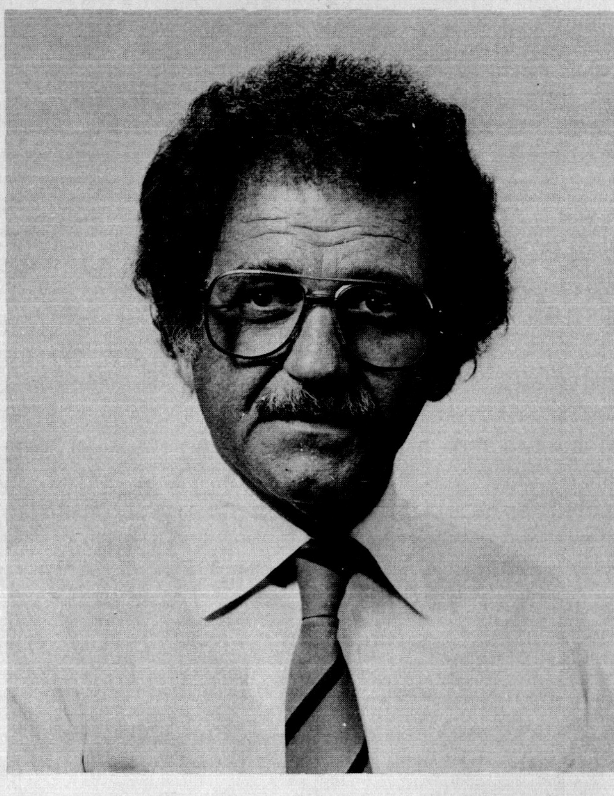
Biography of Magellan Project Personnel

The Magellan Project consists of a small cadre of personnel with an extensive experience base in the conduct of unmanned planetary missions. Brief biographical sketches of some of the Magellan Staff are included here that describe their education and relevant experience. Key individuals making up other elements of the Project will be included in future issues of the "V-Gram".

John H. Gerpheide, Project Manager, has led the Venus Projects, including the Venus Orbiting Imaging Radar and the Venus Radar Mapper missions, for the Jet Propulsion Laboratory (JPL) since 1981.

Since John's joining JPL in 1948, his engineering development activities have included rocket engine and vehicle design, spacecraft development, and solar electric propulsion. Formerly he managed the System Design and Integration Section and, before the Venus Projects, was the Satellite System Manager for SEASAT. He obtained Bachelor and Master degrees from the California Institute of Technology. More down-to-Earth explorations have included two mountain-climbing trips to the Himalayas, one in the Mt. Everest region, and a climb of Mt. Mera.

Anthony (Tony) J. Spear, Deputy Manager since early 1986, is not new to the Venus radar mission. In 1980, he was Project Study Manager for the Venus Orbiting Imaging Radar mission, and then served as Radar System Manager, and Science and Mission Design Manager. In between those assignments, various tasks were carried out for the Department of Defense. With JPL since 1962, Tony was the Sensor Manager on SEASAT, was the Advanced Projects Manager for NASA's Deep Space Network, and held several positions within the Telecommunications Division. Tony holds a Bachelor of Science degree in Electrical Engineering from Carnegie Mellon University, a Master of Science degree in Electrical Engineering from the University of Southern California, and a Master of Engineering degree from the University of California's Engineering Executive Program. He skis the winter slopes, hikes the Sierras in the summer, and accompanied John Gerpheide on two mountain-climbing treks to the Himalayas.



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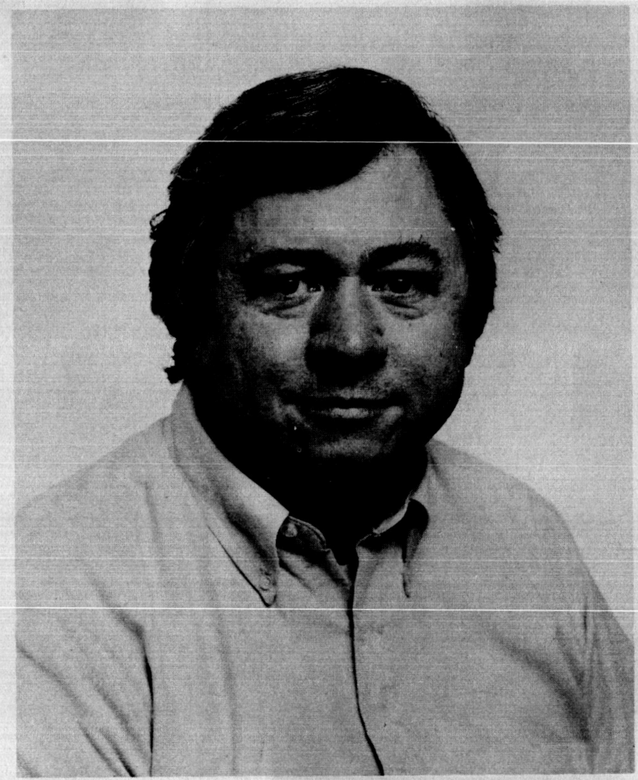
R. Stephen Saunders performs two functions for the Magellan Project--one as the Project Scientist, and the other as a Co-Investigator for the Radar Investigation Group. After joining JPL in 1969, Steve served on the Viking Mission to Mars as a member of the Lander Imaging Team. Since 1971, he has been a Principal Investigator for NASA's Planetary Geology Program, and was a Co-Investigator on the Shuttle Imaging Radar (SIR-A) project.



Steve obtained Bachelor and Doctorate degrees in Geology from the University of Wisconsin and Brown University, respectively. His present research activities are focused on the comparative geology of the terrestrial planets. A former member of the U.S. Peace Corps, Steve served as a geologist in Ghana, Africa. He is active in community affairs, and currently serves as President of the Rotary Club of the city of Altadena. He is also active as a Commissioner for the San Gabriel Valley Boy Scout Council.

THE MAKING OF A PRECEDENT: THE SYNTHETIC-APERTURE RADAR (SAR) ON MAGELLAN

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R. Keith Raney

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Introduction

Astronomical imaging is traditionally done with optical instruments, with spectacular results from several planets accomplished by scanning sensors on dedicated spacecraft. The traditional approach is impractical for Venus, whose atmosphere, opaque at optical wavelengths, requires the longer wavelengths of radar systems for successful imaging. These longer wavelengths require a new approach to the problem of fine-resolution imaging system design.

The classical Rayleigh criterion that describes diffraction-limited performance of apertures such as those used in sensing systems is well known: the lower bound on angular acuity (resolution) is inversely proportional to aperture size. As a result, very large systems have been built to achieve fine resolution, including the 200-inch telescope of Mt. Palomar, or the one-fifth-mile diameter reflector for radio and radar astronomy at Arecibo, Puerto Rico. It is also well known that the Rayleigh diffraction limit is proportional to the wavelength employed. Thus, the large aperture of Arecibo has (at typical radar wavelengths) the same angular resolution as does the human eye, which operates in the visible spectrum.

In apparent contrast to these known facts, a synthetic-aperture radar (SAR) achieves resolution that is proportional to aperture size, and which is not a function of wavelength. One purpose of this article is to give a brief explanation of these properties of synthetic-aperture radar. Philosophically, such systems displace the large-aperture requirement with a large data-processing obligation in order to form a fine-resolution image.

Following the generic SAR discussion, the mission restraints for Magellan are reviewed, and the resulting SAR design is described.

Overview of SAR Systems

It is helpful to trace the form of SAR systems by extending concepts common to scanning imaging systems. If one starts with an optical scanner, three extensions are required in order to arrive at the generic form for SAR.

Assume that we have a scanning sensor mounted on an elevated moving platform, such as an aircraft or spacecraft. Such systems build an image on a line-by-line basis, with a fast scan on each line orthogonal to the platform velocity vector. Since these systems strive to be diffraction limited in both the cross-track and along-track directions, their natural viewing geometry is downward-looking, with spatial resolution (given by the product of angular resolution and scene-sensor distance) degrading as the scan moves away from the sensor ground track. This is the standard configuration for airborne or satellite multispectral scanners, for which the resolution is bounded by conventional diffraction limits.

First Concept Extension

By definition, however, radars used for remote sensing normally achieve resolution in one dimension by measuring time delay, rather than depending on angular resolution. Thus we now extend our scanner to a radar mode, in which a pulse of energy is radiated so as to measure relative time delays of echo components within each reflected pulse. Except for altimetry, the resulting resolution is nearly useless for echoes from the neighborhood of the ground track, but it improves as the scan line extends away from the ground track, simply because the measurement variable (relative time delay) more favorably intersects the ground plane. Thus, the natural viewing geometry for a scanning radar sensor is side-looking rather than downward-looking. The original device for this discussion was a scanned angle/angle sensor. As a result of this first extension, we have a range/angle sensor for which resolution across track (sometimes called range for radar systems) is determined by the length of the pulse radiated, and the resolution along track (sometimes called azimuth for radars) is governed by the width of the radiated pattern, in turn limited by the diffraction limit of the radar antenna aperture. Thus, range resolution could be improved by radiating a shorter pulse, and azimuth resolution improved by using a larger antenna.

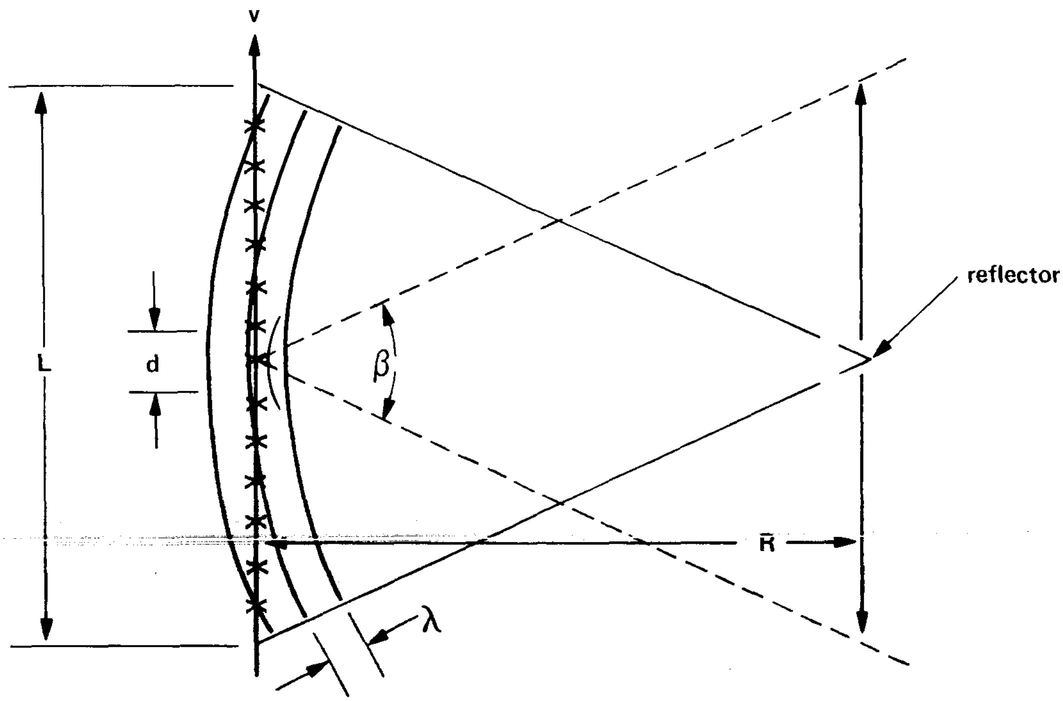
Note that for the radar mode, we no longer require a cross-track scanning mechanism; the radiating pulse scans in range at the speed of light, c, with echoes returning at the same rate. (The effective range scan rate is thus c/2.)

Second Concept Extension

Having a side-looking imaging radar, what is its most important weakness? Clearly, the diffraction-limited, real-antenna aperture cannot be made very large due to physical restraints, so that the along-track or azimuth resolution of the system cannot easily be improved.

However, if the received energy were recorded in memory for a set of successive scan lines, then the data in memory could be processed to achieve a much-improved azimuth resolution, just as if those same scan lines had been simultaneously collected by a much larger antenna. This observation, first proposed by Carl Wiley of Goodyear Aerospace Corporation in 1954, lies at the heart of the synthetic-aperture approach.

Assume that we have a real aperture of (along-track) dimension d meters, which for wavelength λ meters yields a diffraction limited beamwidth β radians, $\beta = \lambda/d$, as in Figure 1. Then a reflector at range R remains within the real beamwidth for a distance $L = R\beta$ (which is the appropriate azimuth resolution of a real-aperture system). The SAR trick is to record the signals received at successive positions "X" as the sensor traverses along V, then to process over the resulting equivalent synthetic array length L. The finest theoretical angular resolution achieved is $\beta_s = \lambda/2L$ (where the factor of 2 occurs in the Rayleigh diffraction limit due to the two-way, phase-sensitive use of the



L = length of synthetic aperture
d = length of radar antenna
v = velocity vector
β = effective beamwidth
λ = wavelength
R = range to target

Figure 1. Plan View of Synthetic-Aperture Synthesis

antenna) yielding β_s = d/2R, with a corresponding along-track resolution r_a (at range R) of half the aperture size, a famous result.

Note that the angular diffraction limit β_s of the synthetic aperture is not a function of wavelength, and is improved as the aperture d is made smaller, both in distinct contrast to the conventional diffraction-limited approach to a real-aperture system.

There are alternative ways to approach this same result. One may view the effect of the motion of the sensor as causing the reflected signal to suffer different Doppler frequency shifts as the beam scans across it. The smaller the aperture, the larger the total Doppler bandwidth produced. And, as is well known from Fourier transform theory, the wider the spectrum, the narrower its transform may be. This fact is the key to the apparent paradox between real-aperture, diffraction-limited systems and synthetic-aperture systems. For a (complex) signal of large bandwidth B and time duration T, we know that the so-called time-bandwidth product TB> 1. Evidently, the azimuth signal duration T = L/V for the geometry of Figure 1. Real-aperture systems are limited by T in achieving azimuth resolution. For SAR's, the system is intentionally designed to achieve TB>> 1, usually through enlarging B by using small antenna apertures. Then the processor must utilize the bandwidth wisely to achieve fine resolution. The image is essentially a transformation of the large time-bandwidth signal.

There are four conditions that must be met by a sensor system in order for the resulting signal to yield successfully to synthetic resolution:

(1) Memory. The signal received at

one point in time is of use in processing only in the context of all other signals received over the required synthetic-aperture length L. This requires memory, and in many applications a very large one at that.

(2) Processor. The set of signals must be processed, even to form an image. One differentiates between the signal history (input to processor) and the images (output from processor).

(3) System Coherence. Individual frequencies may be processed only to the extent that they are present in memory. This requires that the wavefront sampled by the radar as it traverses along the line of flight through the synthetic-aperture length L must have a consistent phase structure. If there are across-track motion errors or timing errors in the system, these must be measured and compensated for to maintain signal coherence. This usually imposes technological restraints on the radar itself, setting SAR systems apart from conventional side-looking, real-aperture radars.

(4) Scene Coherence. Having a perfectly coherent radar is of no consequence if the scene or objects in it have their own random or deterministic motion. **The scene itself must respect phase stability during the time over which the synthetic aperture is formed. If this condition is not satisfied, then curious or disappointing results occur.**

Following the first extension to a conventional angle/angle sensor, we found that range/angle coordinates were the generic form. In the same spirit, the natural coordinates of a SAR resulting from our second extension are range/Doppler, since the variable being exploited to achieve along-track resolution is the variation of Doppler frequency across the real antenna beam. This has important practical consequences for mapping, as in the case of the Magellan mission, since an angle/angle sensor is extremely sensitive to sensor attitude (for example, pitch, roll, and yaw), whereas a range/Doppler sensor is not very sensitive to sensor attitude.

Third Concept Extension

Having now a SAR capable of very fine azimuth resolution, what is its dominant performance limitation? Range resolution, which at this point is governed by the length of the transmitted pulse. We might improve range resolution by shortening that pulse. However, for practical devices, this has the simultaneous effect of reducing the per-pulse energy, so that carried to extreme, one would achieve a very fine resolution image that was too weak to see! Thus, for our third extension we voluntarily employ an artifice analogous to that forced on us in azimuth: namely, we use a large time-bandwidth pulse. The use of such coded pulses in radar has been known for many years, introduced by Darlington of the Bell Telephone Laboratories.

There are many choices available for a suitable range pulse code, but for digital systems, a reasonable choice is to use a known digital code. The code must be designed to behave properly, so that when processed it compresses to a very sharp and single correlation peak, surrounded by minimal secondary maxima ("side lobes") and uncompressed residual energy.

The output of a SAR processor is the image, in which a focused (point) object has a simple shape reflecting the impulse response of the system. Such a simple impulse has time-bandwidth product (TB) = 1. Therefore, a SAR processor's complexity may be measured by the product of the range and azimuth time-bandwidth products of the input SAR signal. Clearly, in order to obtain fine resolution in both azimuth and range from these systems, one is required to translate the consequence of system restraints (antenna size and pulse length) into processing requirements. Once the necessary and sufficient conditions for signal fidelity have been satisfied, the burden of SAR performance falls onto the SAR data processor. (SAR processing is discussed in another article in this "V-Gram".)

Speckle and Multi-Looking

Unlike more conventional imaging systems that rely on non-coherent (phase-averaged) illumination, SAR's depend on coherent (phase-structured) illumination. As an essential consequence, fully coherent SAR imagery has a "speckled" appearance, analogous to that from laser light. This occurs because the elements of the scene being imaged have random phase structure, and interfere with each other in a complex way. The resulting speckle behaves as a multiplicative noise, whose variance is equal to the square of its average value.

The solution to this annoyance is to systematically average "looks" or samples of scene images. If N independent images are formed and averaged, the speckle variance is reduced by N. The catch is that in order to derive independent images, different portions of the original signal must be used. Thus, the available resolution in the image is also degraded by the same factor N. These independent looks may be taken in either the range dimension or the azimuth dimension, and either by time or frequency subset filtering.

Image quality is an elusive concept at best, but one aspect of image quality is its potential information content, which may be formally described in terms of the resolution and number of looks in the image. The appropriate figure of merit is N(range resolution x azimuth resolution)$^{-1}$. This will be readdressed below in the context of the Magellan SAR.

We now are in command of an imaging technology suitable for penetrating the Venusian atmosphere, implementable with an antenna small enough to fit on a deep-space satellite, and capable of very high resolution. It turns out that such an instrument is <u>too</u> good, for it does not fit critical restraints on the mission without further refinement.

The Magellan SAR

There are two driving mission restraints, cost and data rate. It is not enough to do good science. It must be done efficiently and relatively patiently.

Cost

The principal consequences of cost minimization on the Magellan SAR are to require the spacecraft orbit to be elliptical, and to restrict the choice of SAR antenna to an existing communication antenna (from the Voyager program). Whereas these may sound like rather benign matters, they have forced considerable creativity into the SAR design.

Antenna

The key element in any imaging radar design is the antenna. It determines coverage, ultimate resolution, minimum data rate, and required transmitter power. For Magellan, the required antenna is a 3.7-meter dish, rather a long way from the larger, highly asymmetric antennas normally favored for such SAR's.

The range coverage dictated by this antenna size in elevation is consistent with the width of swath required for each orbit, so that each successive pass images adjacent Venusian surface. (The orbital period is designed to be about three hours so that the slow rotation of Venus achieves the desired change in swath position.) So far, so good.

In the other direction, the antenna size has more impact. The theoretical azimuth resolution available from the Magellan antenna is about two meters, nearly 100 times finer than other system restraints allow. Such phenomenal resolution is available only if all the radar data are gathered, transmitted to Earth, and processed. For Magellan, in which azimuth resolution of about 120 meters is planned, the radar will be operated in a burst mode, in which only about one-tenth of the available data will be gathered, thus saving radar power, and helping to meet the data-rate restraints discussed below.

The SAR antenna serves a dual purpose, as it is also used in the non-imaging part of each orbit to relay instrument data back to Earth.

Orbit

For reasons directly available from orbital mechanics, it is much less expensive to use an elliptical orbit at Venus rather than a circular one. The fact that it is easier to operate a SAR from a circular orbit is nearly immaterial. Thus, the Magellan SAR has been designed to adapt to variations in relative altitude from approximately 2000 km to 250 km and then back up to 2000 km, gathering data only in that portion of the orbit closest to the planet, as shown in Figure 2. Such a variety of operating altitudes has impact on both radar control and timing, and on the resulting imagery.

Since the radar is operated in burst mode, it is convenient to preset the appropriate SAR control parameters for each burst. This requires a rather careful analysis of the geometry of flight and derivation of the required commands to be done by the Radar Mapping Sequencing Software. The result is a set of about 1000 unique configurations to adequately put the Magellan SAR through its paces for each orbit. It is expected that these commands will be preloaded into the SAR controller for each three-day interval during the mapping period.

In order to minimize the effect of the ten-fold altitude change on SAR imagery, the mission has been designed to operate with a variety of incidence angles through each mapping pass. By starting at high altitude with steep incidence, swinging out to more shallow incidence at lower altitudes, and then back to steeper incidence angle as the altitude increases again, the impact of altitude change is partially offset. The resulting geometry is favorable in two additional ways. First, at shallower incidence angle the effective range resolution on the surface is improved over that at steep incidence. Second, at steep incidence there is more time available to gather redundant data for extra looks, thus providing a potential improvement to offset the loss of range resolution. These geometrical effects have been elegantly balanced for the Magellan SAR, as summarized in Table 1. Please note that the image quality (bandwidth) factor varies only about plus or minus 5% over the full range of imaging altitudes.

Incidence angle effects will be important, as noted in previous "V-Grams".

Data Rate

The Magellan SAR data must be relayed from Venus to Earth via NASA's Deep Space Network (DSN). This major communication system imposes a working limit of about 270 kilobits per second on the SAR data stream.

Whereas this may seem rather large, it is miniscule by SAR standards. For example, the equivalent digital data rate for SEASAT SAR was 120 megabits per second. Since the objective is to substantially image the planet Venus, within a time restraint and with rather high resolution, the DSN data-rate limit is the toughest requirement on the entire system.

Data rate is proportional to the image quality factor, swath width, spacecraft velocity, and number of digital bits per data sample. (Data rate is eased if the data can be buffered and played back more slowly, which is already built into the Magellan mission design, another advantage yielded by the elliptical orbit.)

The only degree of freedom remaining in the data-rate budget that has not been fixed by coverage, resolution, or orbital mechanics, is the number of bits for each sample. These budgets imply that only two bits per sample are available for the SAR data.

What, a two-bit SAR? Yes, and again the unique characteristics of a SAR, together with digital data innovation, make this an acceptable solution for Magellan.

The innovation is to use a digital automatic gain-control technique to use to best advantage the small number of digital bits available. The Block Adaptive Quantizer (BAQ) developed for Magellan allows a much wider dynamic range of SAR data to be transferred on the DSN than two bits per sample suggests. This follows because the average radar signal strength changes slowly, due primarily to the large antenna beamwidth, and to the rather long

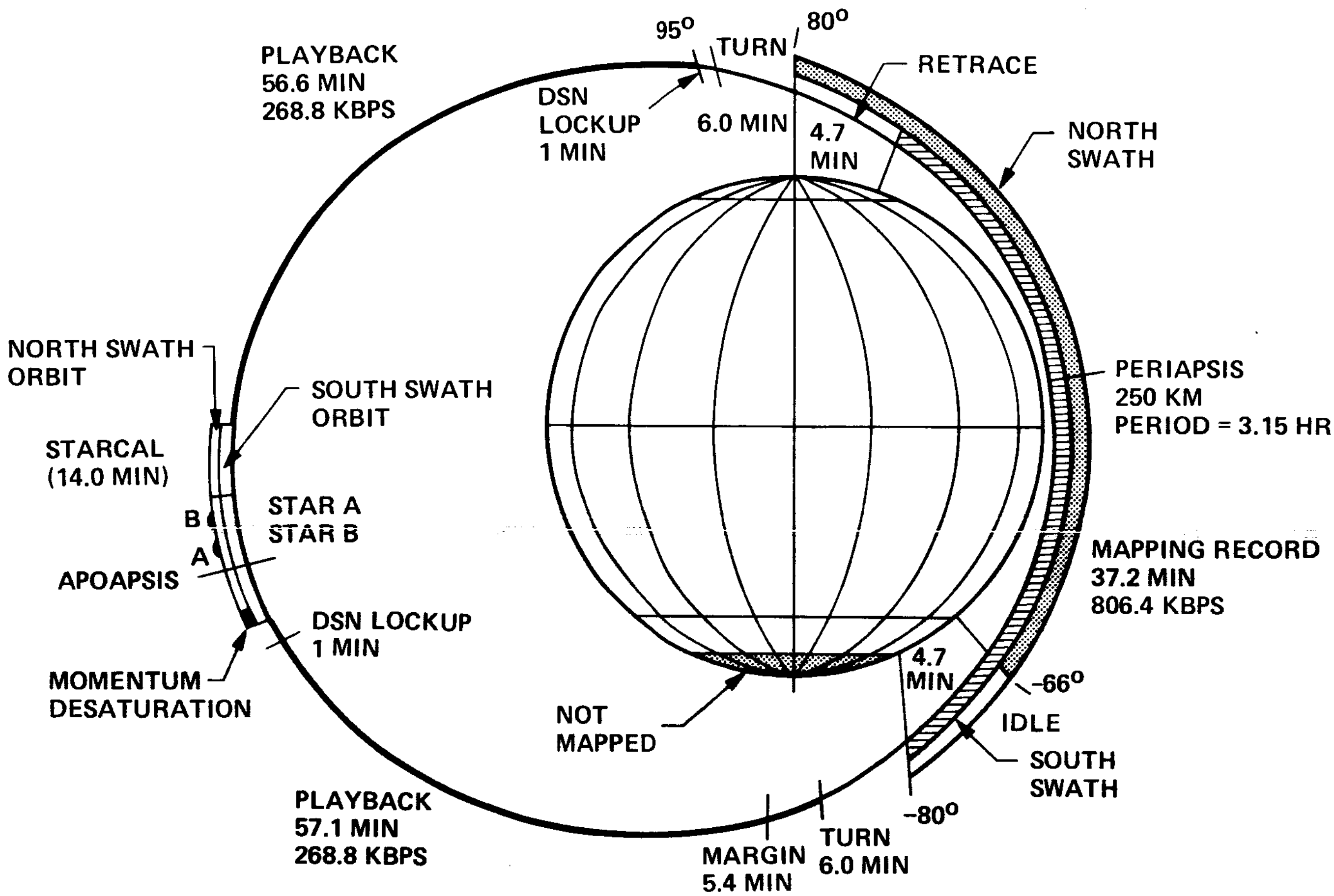


Figure 2. Magellan Orbit Layout and Alternating Swath Strategy.
(Angular values are measures of true anomaly.)

Table 1. SAR Geometrical Performance

ALTITUDE (km)	INCIDENCE ANGLE	RESOLUTION			QUALITY $N(r_g \times r_a)^{-1}$
		RANGE	AZIMUTH	LOOKS	
250	52	110	122	4.8	3.6 E-4
500	39	137	121	6.0	3.6 E-4
1000	28	181	121	8.5	3.9 E-4
1750	21	247	120	11.6	3.9 E-4
2100	19	270	120	13.5	4.0 E-4

coded pulse in range. Indeed, we have come nearly full circle, for the reasons that led originally to large data-processing requirements in the evolution of the SAR concept are the same reasons that a rather simple digital gain control and a small number of bits per sample are sufficient to support the required SAR data transfer.

The BAQ is discussed in greater depth later in this "V-Gram".

Conclusion

Out of necessity, a radar has evolved for Magellan that is innovative. It is aggressive in its concept, demanding, yet feasible in its realization, and promises remarkably stable data over a wide variety of conditions to support the science objectives of the mission. Most of the design and engineering elegance of this instrument will be invisible to the end user, which, after all, is one characteristic of the best scientific instrumentation.

Acknowledgements

The author, on behalf of the Magellan Project Science Group and the Radar Investigation Group, expresses special thanks to W.T.K. Johnson and the radar team at the Jet Propulsion Laboratory, and to the radar contractor, Hughes Aircraft Company, for the work represented by the Magellan SAR.

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SAR SYSTEM TEST AND CALIBRATION

17.

R. Keith Raney

Introduction

The System Calibration and Test Task Group of the Magellan Project Science Group (see "V-Gram" No. 8, March 1986) is responsible for monitoring the radar test procedures and associated support equipment established by the Project and its contractors. This Group is also responsible for monitoring quality assurance of the SAR data products generated during the mission. While not carrying the prime responsibility for the performance of the radar system, the Group will provide advice from the users' point of view, and will attempt to make sure that calibration and data quality of the radar are sufficient to meet the needs of the scientists.

This article is intended to provide an overview of the issues involved. The end objective of the Magellan radar imaging mission is to provide high-quality map products of Venus for science investigations of the planet. By implication, assurance of stable, accurate, and high-quality map image products embraces nearly all aspects of mission and system design which, of course, are responsive to the science requirements placed on the Project.

Calibration

The Magellan images, whether in digital or photographic form, will consist of a mapping of brightness estimates just as in any image. The brightness estimated by the radar flight instrument and ground-based processor--the radar system--corresponds to reflection by the surface of the microwave energy emitted by the radar. Radiometric calibration is desirable so that image brightness variations are a faithful representation of the actual microwave reflectivity variations observed by the instrument. Spatial calibration is necessary so that the reflectivity information is placed consistently and correctly onto a map coordinate system of the planet. Each of these two aspects of calibration implies rather different system and mission considerations.

Spatial Calibration

Accurate location of radar data over Venus--the mapping problem--consists of a nested sequence of logical reference positioning: location of the orbit relative to the surface; location of the image relative to the spacecraft; and location of points within the image relative to a nominal reference point. Absolute spatial calibration requires knowledge (to a specified tolerance) of the first two of these stages on a single orbit basis.

Relative spatial calibration refers to the fidelity of mapping accuracy between points in a given frame or sequence of frames of data, and to the fidelity of placing subsequent orbits together to build a mosaic or composite map section.

The planned orbit sequence to provide the base map of Venus is shown in Figure 1 plotted against a sketch Mercator projection of the planet. It is the responsibility of mission control, navigation, and tracking to maintain knowledge of spacecraft ephemeris during the mapping phase.

Location of the image relative to the spacecraft is the most interesting aspect of the spatial calibration problem. The good news is that a range-Doppler radar, such as the SAR on Magellan, has a natural coordinate system that lends itself to accurate image positioning. Optical sensors, such as the Thematic Mapper, use angular coordinates relative to the spacecraft inertial frame to locate image data; hence such systems are very sensitive to angular rotations of the spacecraft. These spacecraft orientation tolerances are usually the dominant source of errors. The Magellan SAR image location is not sensitive to spacecraft rotation errors since the mapping coordinates are time delay (measured in distance away from the spacecraft) and Doppler shift (determined by spacecraft velocity, and measured in along-track plane of the orbit). Thus, one may expect the radar to provide excellent accuracy of image placement relative to the Magellan spacecraft.

The bad news is that the elliptical orbit of Magellan (see Figure 2, Page 9) requires very careful analysis and parameter tracking in order to achieve the theoretical accuracy. Both the range to the surface from the spacecraft and the velocity of the spacecraft along the orbit change during each mapping record so that the critical

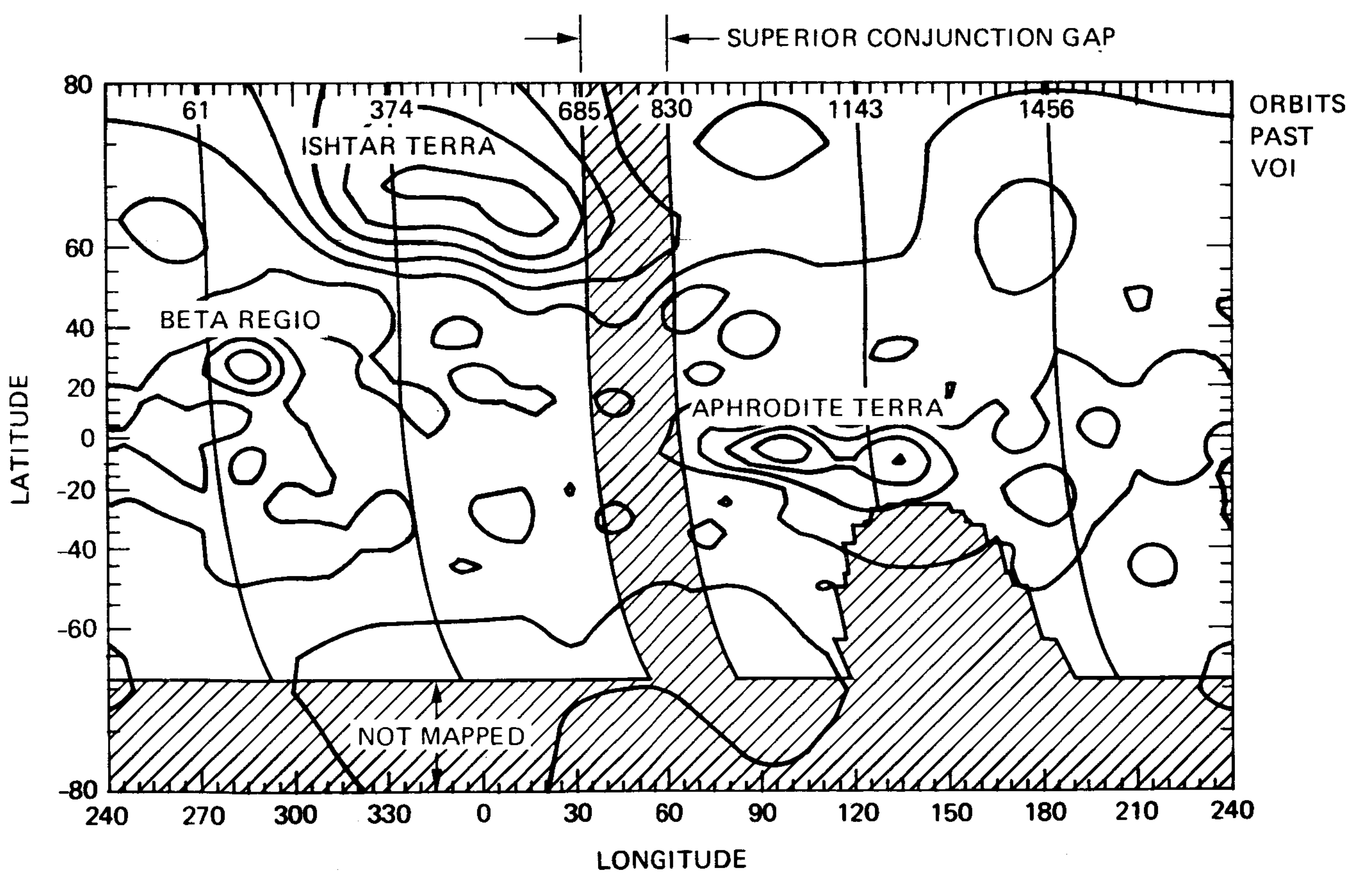


Figure 1. Magellan Orbit Ground Track

scale factors in each of the two dimensions of the generated image are constantly varying. Furthermore, except at periapsis, the minimum range plane to the planet surface is not orthogonal to the spacecraft velocity vector; hence the so-called zero-Doppler angular position cannot be used directly to reference the image location to the spacecraft location. Fortunately, the parameters required to control the radar and to locate its imaging window are the same ones required to control the data processing, so that accurate image location is possible. It is a matter of adroit engineering, data handling, and tolerances.

Accurate location of data within an imaged frame relative to a reference position is not trivial. In the range direction, time delay is converted into nominal surface position using the spacecraft/surface geometry pertinent to each burst, for which the key parameter is incidence angle. At the spacecraft, this translates into the side look-angle (away from the orbital plane) as shown in Figure 2. Thus, each frame of data has its own range scale factor, one which is also range-dependent.

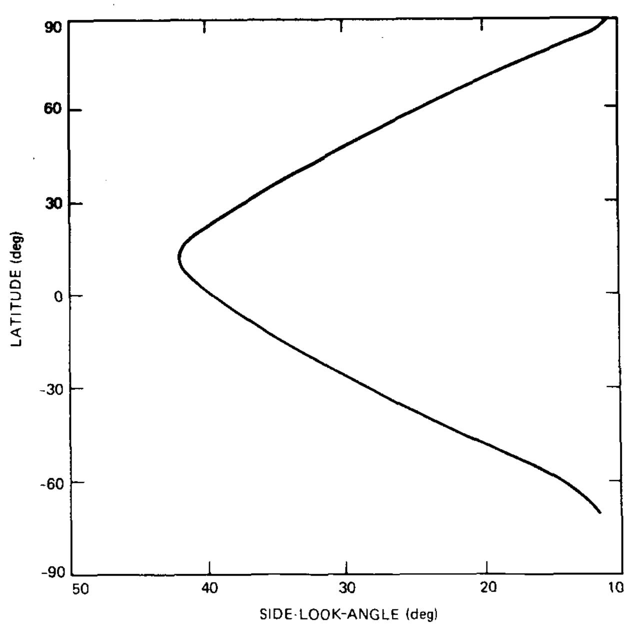


Figure 2. SAR Look-Angle vs Venus Latitude

The range mapping accuracy is further complicated by variations in terrain elevation from the nominal surface contour assumed. This so-called elevation displacement is a known phenomenon in oblique imaging systems, and allowance has been made for it in performance requirements for Magellan.

In global mapping, the Venusian surface profile deduced from Pioneer Venus and other sources will be used to compensate for major terrain elevation changes.

In the azimuth direction, the mapping coordinate is derived from the differential Doppler shift data along the frame which is scaled both by spacecraft velocity and nominal range to the imaged surface. Since this mechanism is quite different from the time delay used in range, considerable care must be exercised to assure that the azimuth and range imaging scales are the same within the required tolerance.

For those frames in which the image is not derived from azimuth data that are clustered about zero-Doppler frequency, it is required to know the mean Doppler offset frequency of the data. Errors in this parameter will result in non-orthogonal image coordinates appearing as a skew distortion, and in errors of image placement and scale along-track over the mapping record.

Radiometric Calibration

The radar image delivered to a user for scientific interpretation is intended to present brightness as a variable, dependent only upon scene characteristics such as roughness, slope, or dielectric constant. In between the scene and the science is the system--which may impose unwanted variations on the image radiometrics. It is the task of radiometric calibration to minimize and quantify these system-dependent variations in brightness.

Major system elements that impact radiometric calibration are: antenna, in absolute gain and in relative gain in both principal planes of the pattern; radar range from the sensor to the scene element being imaged; electronic signal levels and gain of the transmitter and receiver, including level adjustment of the two-bit automatic gain control (AGC) in the signal downlink formatter; and processing gain in the ground-based image formation facility.

Antenna. Since the radar antenna is used for both transmission and reception of imaging data, it appears in the calibration equation as gain squared. This is the most sensitive and critical parameter in the calibration budget. It should be clear from the discussions above that during each imaging pass, different geometries and hence different portions of the antenna pattern are used. These, although principally selected by the RMSS as a part of the initialization for each imaging burst, may be fine-tuned and optimized in the data processor at the time of image processing. Planning for verification and calibration of the antenna pattern is an ongoing activity of the Project, and now seems to be in hand.

Range. As with other imaging radars, the impact of range on the calibration budget is (approximately) as inverse cubed. Unknown variations in range could have a large impact on the measured signal brightness, yet it is not expected to be a major source of error for the Magellan mission, due largely to the tightly controlled range window of rather small extent. Placement of the imaging range window (in time delay) relative to the elevation antenna pattern as it intersects the planet surface is a more critical parameter, included in the antenna discussion above.

Radar Gain. Unlike most of the other parameters that enter the calibration link budget, radar gain, both the level of the transmitted signal and the gain of the receiver chain and AGC, may be monitored directly by observation and use of the spacecraft engineering data. The crucial issue is to maintain adequate and stable levels throughout the operative lifetime of the mission. With relatively low-power, solid-state electronics and good space-qualified implementation, radar gain should not be a major stumbling block in achieving adequate system calibration.

The Block Adaptive Quantizer (BAQ) interacts directly on the signal level, and so its effective gain is included in the signal record as well as the engineering data record.

Processing Gain. As described in the previous article, the image processor is an integral part of the radar system, and as such it is crucial to the calibration budget. Its impact is second only to that of the antenna pattern. Being on the ground, it can be monitored, tested, verified, and qualified perhaps more completely than other elements of the system. However, the processor must have baseline parameter sets in variety sufficient to match the data-gathering modes of the radar which, as may be recalled, number nearly 1000. Furthermore, the processor may be called upon to render certain "corrections" on the data, such as Doppler or range window weighting, which will have impact on the gain stability and fidelity of the system. For these reasons, the sheer variety and capability of the processor make it difficult to calibrate and monitor adequately.

Requirements on Calibration

From the foregoing it should be clear that calibration of the Magellan SAR is a challenge, both spatially and radiometrically.

The spatial calibration requirement is summarized by the seam mismatch tolerance on pass-to-pass mosaicking, specified to be less than 500 meters. It is expected that this requirement will be met.

The radiometric calibration requirements are that absolute radiometric calibration must be better than within 5 db, and that relative radiometric calibration for a 1000 km swath length should be within 2 db. (For terrestrial applications of SAR's in circular orbits, the corresponding state-of-the-art performance is about half of those numbers.) Again, it is expected that the radiometric calibration requirements will be met.

Mission Profile

The objectives and principal issues for calibration of the Magellan SAR have been outlined above. Satisfactory results can be achieved only if calibration and the parallel objective of stable high-quality data are consciously pursued from Project conception to completion. Key aspects of calibration are outlined here against the Magellan development and mission timeline.

For a system such as the Magellan SAR, it is impossible to fully test, much less to calibrate, it prior to launch. Although the SAR is essentially a straightforward radar, the geometry imposed by the Venusian orbit, and the extensive variety of operating modes imposed by that geometry make complete testing out of the question. At the time of launch, full confidence in the SAR will have been assured by a rigorous plan of verification, relying on subsystem tests, simulation, and analysis, all of which are standard procedures for such deep-space missions--yet the radar will not have produced a single image.

The period from launch to end of mission (shown in Figure 3) includes several activities crucial to successful calibration of the SAR. During the cruise phase, several opportunities are planned to verify the pattern of the SAR antenna, and to calibrate its gain in the free-space, far-field environment. The antenna is used both for the radar at S-band and for the downlink of telemetry at X-band. Thus, the 3.7-meter reflecting dish is fitted with two feeds, one at each frequency. Since the antenna is such an important part of the calibration budget, quantitative observation of the actual beam pattern is essential.

The radar modes will have been exercised in software and with simulation prior to launch. The first opportunity to observe the actual operation of the SAR and to test and calibrate its sequencing controller will be at Venus, scheduled during the first few days following Venus orbit insertion (VOI). That period (approximately eight days) will be used to test and calibrate the spacecraft systems

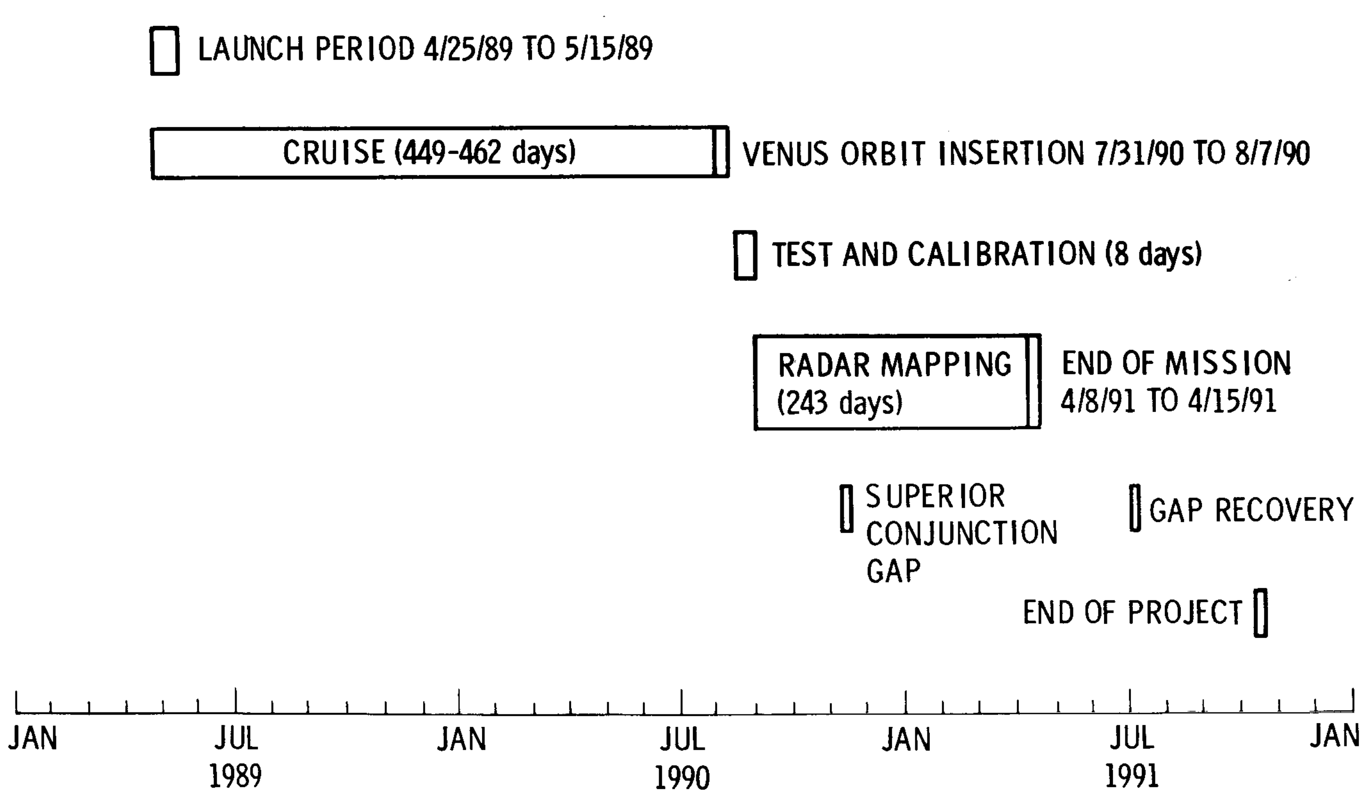


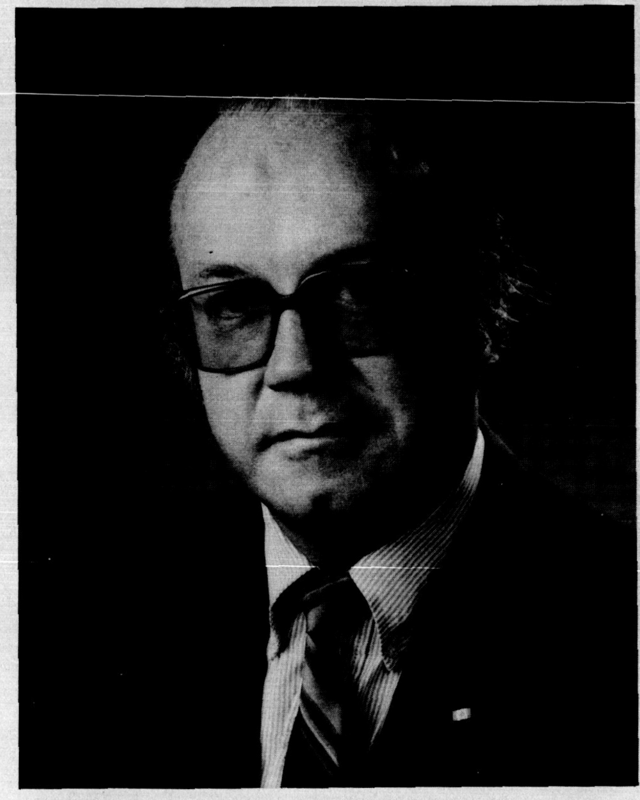
Figure 3. Magellan Mission Timeline

and the radar sensor, in addition to trimming the orbit to the desired period, periapsis altitude and location, and inclination. The Radar Mapping Sequencing Software (RMSS) will also be checked out during that period to determine its ability to translate performance requirements and navigation orbit predicts into correct data-collection commands. Since the required timing on the radar is so tightly coupled to the actual timing and orbital parameters achieved, this phase will be very busy. The SAR imaging and supporting data that will result will be of much more interest to systems engineers than to scientists. The objective of this mission phase is to have several iterations of the data-collection and data-processing operations, so that the system can rapidly converge on an operational scenario that will be used for the following 243 days.

Following the test and calibration phase, the SAR as an instrument will have been calibrated and will be qualified to perform its mapping function. However, this is not sufficient to assure that the image data to be delivered is itself calibrated for the scientific purposes of the mission. Full calibration in the spatial and radiometric sense is an ongoing responsibility of the Project. Plans are now being completed to provide for the scientific calibration of the data, and to underwrite full quality assurance of the data products.

About the Author

R. Keith Raney worked with the Environmental Research Institute of Michigan (formerly the University of Michigan, Willow Run Laboratory) from 1963 to 1976, and was active in moving-target indicator (MTI) radar, synthetic-aperture imaging radar, and optical data-processing techniques. Since 1976, he has been with the Canada Center for Remote Sensing, Ottawa, Ontario, with major responsibilities for airborne and satellite radar programs. Currently, Dr. Raney is Chief Radar Scientist for the Canadian RADARSAT Program, which is working toward an operational imaging radar mission for Earth resource applications for the early 1990's. He has served as a Consultant to NASA, ESA, and the United Nations, and to United States, Canadian, and foreign industry on radar matters. He contributed to the Pioneer Venus radar, was radar specialist for the Venus Orbital Imaging Radar science team, and contributed to SEASAT SAR and the Shuttle imaging radars. He has lectured in advanced imaging radar courses in Italy, Austria, Israel, the United Kingdom, the United States, and Canada.



Dr. Raney is a member of the Canadian Remote Sensing Society, an Editor for the International Journal of Remote Sensing, and an Editor and Vice President for the IEEE Geoscience and Remote Sensing Society, and serves on various committees for the International Astronautical Federation, International Society of Photogrammetry and Remote Sensing, the International Geophysical

Union, and the International Union of Radio Science. He received a B.A. degree in Physics from Harvard, an M.S. in Electrical Engineering from Purdue University, and a Ph.D. in Computer Information and Control Engineering from the University of Michigan. Dr. Raney is active in Science for Peace in Canada, and with his family enjoys sailing, particularly in the beautiful remote islands of Lake Huron's North Channel.

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MAGELLAN RADAR SYSTEM DESIGN

William T. K. Johnson

Introduction

The design of the Magellan radar system was dictated in many ways by the mission constraints. A combination of factors led to the major mission constraints listed in Table 1. The elliptical orbit and small antenna (compared to Earth-orbiting SAR's) are the most demanding constraints from a radar system design view. The requirement on the design was to meet all science objectives within the mission constraints. The design has to make very efficient use of each of the limited resources, especially data rate. The mission must also complete all its objectives in one Venusian day (243 Earth days).

Table 1. Mission Constraints

1. Elliptical Orbit with Period 3.1 to 3.7 hr.
2. Periapsis Altitude: 250 to 300 km
3. Voyager Antenna: 3.7 m (shared with Telecommunications)
4. Data Record Rate: 806 kbps
5. Data Volume per Orbit: 1700 Mbits
6. Data Rate to Earth: 270 kbps
7. No Real-Time or Near Real-Time Commanding
8. Low-Cost Mission Operations
9. Use Existing Digital Processor

The absence of real-time command capability and the desire for a simple radar dictate the use of navigation data to set the radar data-collection parameters. The radar is commanded by the spacecraft from repetitive sequences stored in the spacecraft command memory. These sequences are calculated from navigation predictions and uploaded to the spacecraft three times a week.

The sharing of the rigidly mounted high-gain antenna (HGA) means frequent turns of the spacecraft for mapping and communications with Earth, along with star sighting for navigation. This sequence is repeated every 186 minutes, as shown in Figure 1. Because a great deal of redundant data is acquired near the poles, alternate passes are biased north (orbit A) or south (orbit B). The spacecraft accomplishes the turns with the required high accuracy through a reaction wheel system. Even with all the turning, very little consumable liquid propellant is used which would limit the mission life.

The spacecraft, including the high-gain antenna, is an assembly of many parts from previous planetary missions, mainly Galileo and Voyager, while the radar sensor equipment is new. Most of this equipment will be designed and built by Hughes Aircraft Company of El Segundo, California, under contract to JPL. JPL will build the PRF and Timing Unit, as well as the Data Formatter Unit.

System Design

The inherent high data rate of the SAR system must be reduced to satisfy the fixed data-rate constraint imposed by elements of the data handling and transmission system. As shown in Figure 2, the radar employs a "burst mode" data-collection scheme. The burst mode is a time domain data-reduction method in which the transmitter is turned off periodically. This figure also shows the methods used to reduce the high instantaneous data rate. The echo is quantized initially to eight bits in two channels at a sampling rate of 2.26 MHz. These data are then passed through the Block Adaptive Quantizer (BAQ), discussed later, which reduces the data by a factor of four. The data are initially in a

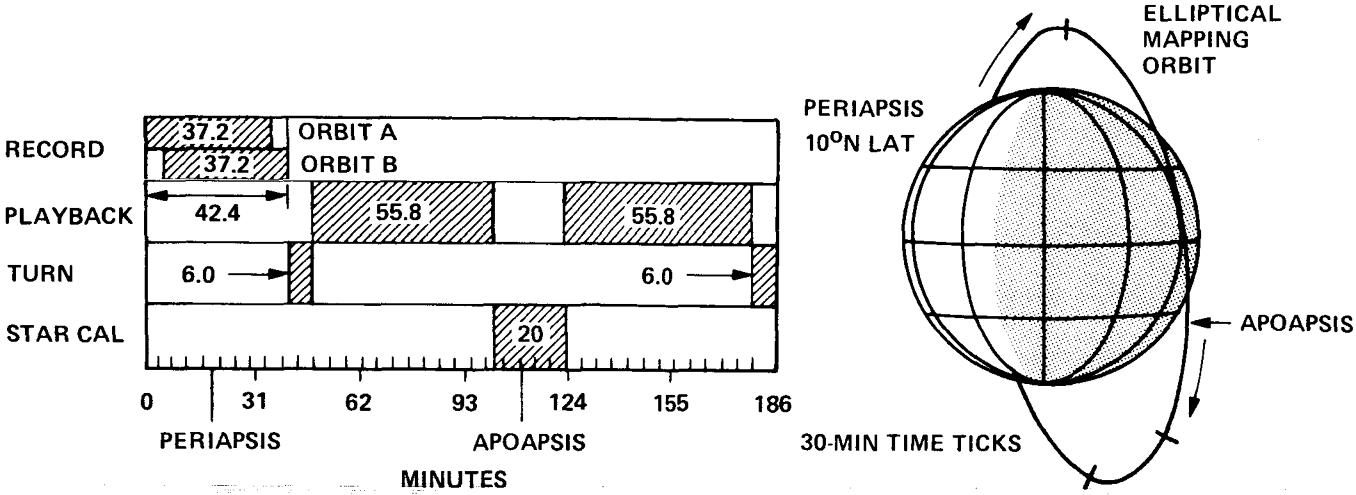
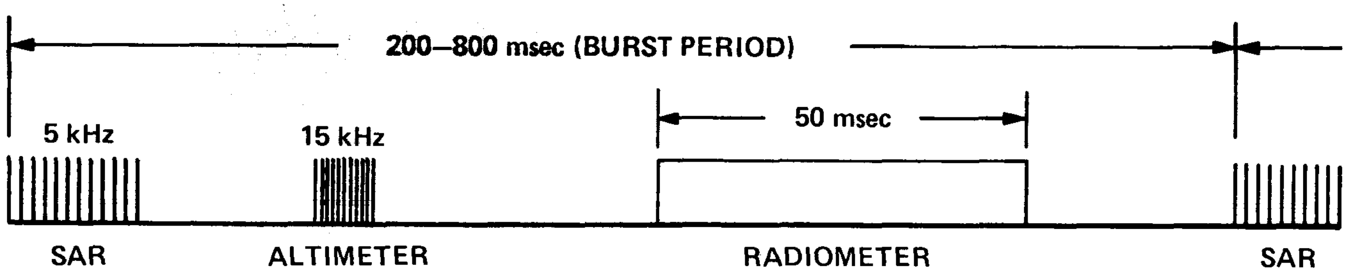


Figure 1. Mapping Timeline and Orbit Geometry



INSTANTANEOUS DATA RATE (BITS/SAMPLE x CHANNELS x SAMPLE RATE)

$8 \times 2 \times 2.26 \times 10^6 = 36.2 \times 10^6$ BITS/SEC

USE BLOCK ADAPTIVE QUANTIZER (INSTANTANEOUS DATA RATE x BAQ FACTOR)

$36.2 \times 10^6 \times \frac{2}{8} = 9.05 \times 10^6$ BITS/SEC

BUFFER INTERPULSE AND BURST (REDUCED DATA RATE x BURST DUTY FACTOR)

$9.05 \times 10^6 \times 0.088 = 0.806 \times 10^6$ BITS/SEC

WITH 37.2 min RECORD AND 112 min PLAYBACK (AVERAGE RATE TO RECORDERS x RECORD TIME/PLAYBACK TIME)

$0.806 \times 10^6 \times \frac{37.2}{112} = 0.268 \times 10^6$ BITS/SEC

Figure 2. Burst Mode Process and Data Rate Calculation

buffer memory and are then sent at a constant rate to a spacecraft tape recorder. Later in the same orbit, the recorded data are played back at a slower rate for transmission to Earth.

The above reduction in data rate had to be accomplished without significant loss of image quality. SAR image quality can be described by five parameters: number of looks, spatial resolution, amplitude resolution, signal-to-noise ratio (SNR), and incidence angle. These parameters are not independent, and a balance must be achieved to satisfy all these requirements within the mission constraints.

Looks. The "looks" in a SAR system are needed to reduce the coherent noise, or speckle, associated with images derived using coherent illumination. The looks are independent observations that reduce the azimuth resolution by a factor equal to the number of looks. For Magellan SAR, the looks are taken by using each burst of SAR data for a single look.

Spatial Resolution. The range (across-track) and azimuth (along-track) resolutions for a SAR are individually selectable. The range resolution is determined by the transmitted bandwidth. The azimuth resolution is independent of radar bandwidth and is determined by the length of the "synthetic aperture" created while moving past a target.

Amplitude Resolution. The amplitude resolution of a SAR system is the ability to produce an output image with amplitude proportional to the radar backscatter coefficient of the surface. A large dynamic range is associated with a large number of bits per sample, but since the data rate is of critical importance here, a new method was employed to achieve large dynamic range while using fewer bits: the Block Adaptive Quantizer (BAQ). The BAQ accepts input data in the form of eight bits, sign plus seven-bits magnitude, and outputs two bits, sign plus one-bit magnitude. The one-magnitude bit is selected to be either 0 or 1 through a threshold detect system which sets the threshold level by averaging the input data in blocks across the echo. The threshold information is combined with the selected bits in the ground processor to reconstruct the original data as accurately as possible. One consequence of burst mode is the need for a memory in the radar of sufficient size to contain all the bits from one complete burst so that a constant rate of data is sent to the spacecraft recorders.

Signal-to-Noise Ratio. The required thermal signal-to-noise ratio (SNR) for the system was chosen to be 8 db, based upon several simulation studies of images at various SNR's and quantization levels using real SAR data. For a 2-bit quantization level and more than four looks, higher values of thermal SNR were difficult to discern and lower values degraded the images. The system SNR, which includes the sum of all noise contributors such as thermal noise, ambiguities, saturation and quantization noise, noise associated with the processor, and link error noise effects, is about 5 db in the output image.

Incidence Angle. The incidence angle is the angle between the radar beam and the normal to the surface. It is an important parameter in image interpretation. If the angle is too shallow, the images suffer from foldover, in which high-relief areas fold toward the radar. If the angle is too high, portions of the images are shadowed by areas closer to the radar. High angles also suffer from low backscatter. Between the two extremes of about 20 and 70 degrees of useful incidence angle is the region of scientific interest. For most geologic use of the data, angles of greater than 30 degrees are desirable and, from an engineering point of view, angles less than 50 degrees are mandatory for Magellan.

Based on the general scientific desire for higher incidence angles than are technically possible, the radar will operate at the highest angle possible, commensurate with satisfying the other image quality requirements at each altitude. The radar incidence angle in the present design varies from about 20 degrees at the pole to about

50 degrees at periapsis. Because of the location of periapsis near the equator, about 70% of the planet's surface will be imaged with an incidence angle greater than 30 degrees, which satisfies the science requirements.

Radar System

The radar system is comprised of the radar flight equipment, the radar data-processing subsystem, and those elements in the Spacecraft Flight System, the Deep Space Network (DSN), and the JPL Mission Operations System that are involved in uplink command and control and downlink transmitting and recording of the radar data stream. The radar flight equipment consists of the sensor and the altimeter antenna. Figure 3 illustrates the spacecraft and the radar system block diagram.

The Magellan spacecraft, a modified Voyager bus, transports the sensor subsystem and antennas along an interplanetary trajectory. It then inserts itself into a 3.15-hour, nearly polar, elliptical orbit around Venus, with a 250 km periapsis altitude at 10 degrees north latitude. Mapping commands, generated on the ground, are relayed to the sensor subsystem by the spacecraft command and data subsystem. The sensor subsystem can operate up to an altitude of 3500 km sending radar data containing SAR, altimeter, and passive radiometer data to the spacecraft tape recorders for storage. During the remainder of the orbit (near apoapsis), the spacecraft reorients itself toward Earth, and the radar data and engineering telemetry are transmitted to the Deep Space Network via the same 3.7-meter parabolic high-gain antenna used for

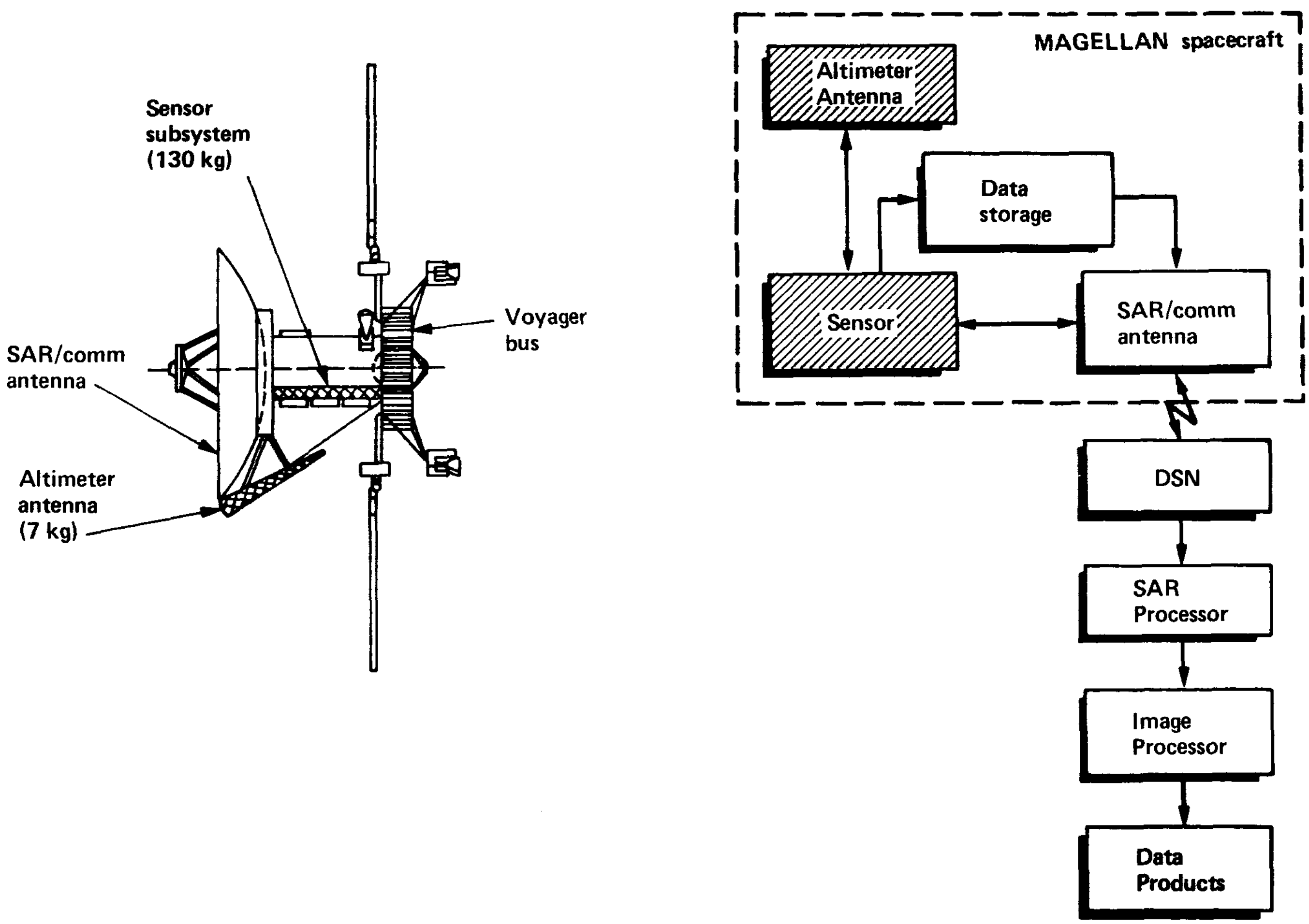


Figure 3. Magellan Radar System

mapping. The radar data are subsequently processed into image data records. The altimeter and radiometer data products are generated by the Multimission Image Processing Laboratory at JPL, which also mosaicks the image data records from each mapping pass into large maps.

Radar Flight Equipment

The sensor subsystem implementation blends many electronic domains, including dc power conversion, microwave pulsed power, low-noise microwave amplification, RF and video amplification, analog-to-digital conversion, coding, and digital data formatting, and employs many digital logic families, including ECL, Schottky, low-power Schottky, and CMOS. The sensor subsystem mounts to the spacecraft in one mechanical assembly. Subsystem electrical interfaces with the spacecraft include power, command, telemetry, radar transmission, RF digital reception, and the radar data stream.

The sensor subsystem is partitioned into the units shown in the Figure 4 functional diagram. Each unit has clearly defined elements grouped on the basis of similarity of function. The sensor subsystem is comprised of redundant, cross-strapped units. Circuit replacement is accomplished at the unit level. The unit functions are shown in Table 2.

Units are packaged in one or more modules. A unit is defined to be nonredundant; thus two units of each function are flown in the sensor subsystem.

Table 2.

PRF and Timing	Generate stable timing and clocks
Range Dispersion	Generate coded S-band signal
Transmitter	Amplify S-band signal
Output Network	Connect transmitter/antenna/receiver; monitor forward/reverse power
Receiver	Amplify low level echos and planet emission; provide first downconversion and gain control
Baseband Processor	Provide downconversion and digitization to 8 bits
Data Formatter	Select two bits in BAQ; buffer high rate radar data; create radar data stream
Telemetry and Command	Accept spacecraft commands and time; issue commands to radar units; process radar engineering telemetry

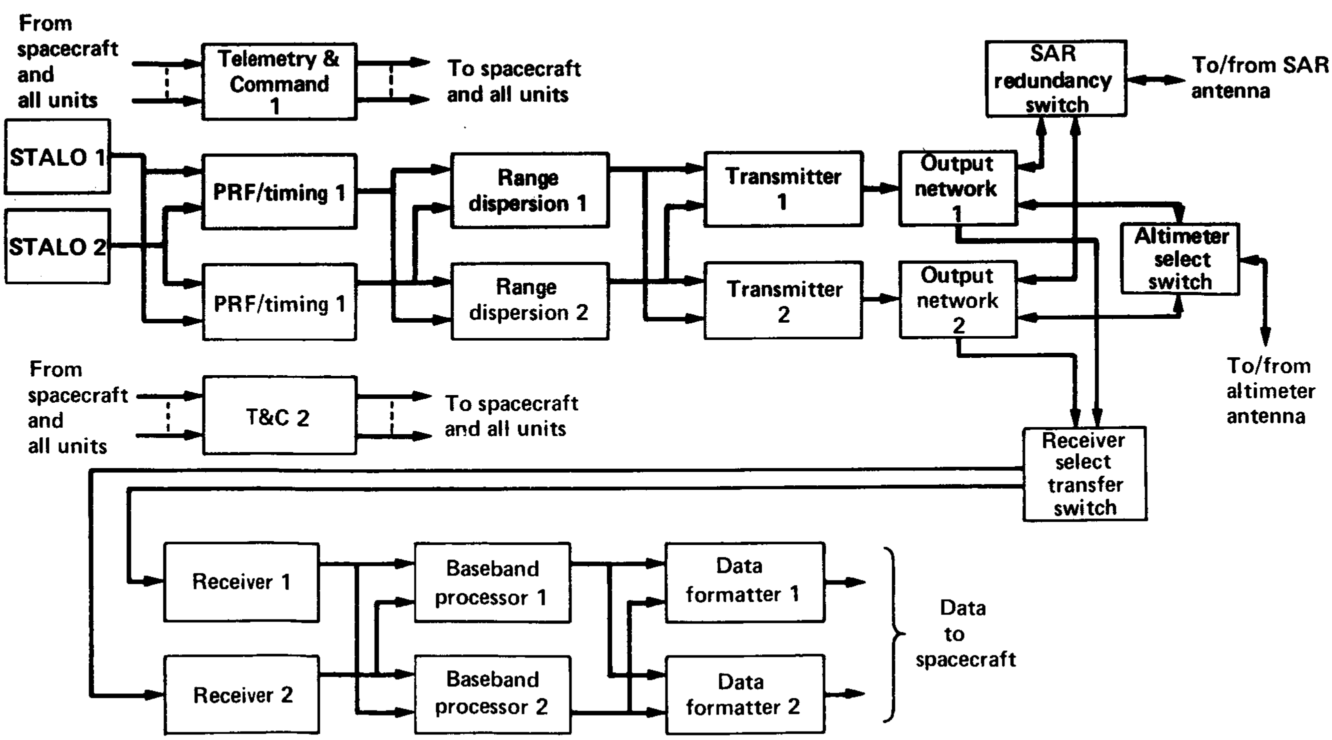


Figure 4. Sensor Subsystem

Figure 5 shows the sensor subsystem layout. The sensor subsystem mass is 137 kg and draws 220 watts during mapping. Sensor dimensions are 135 by 85 by 33 cm.

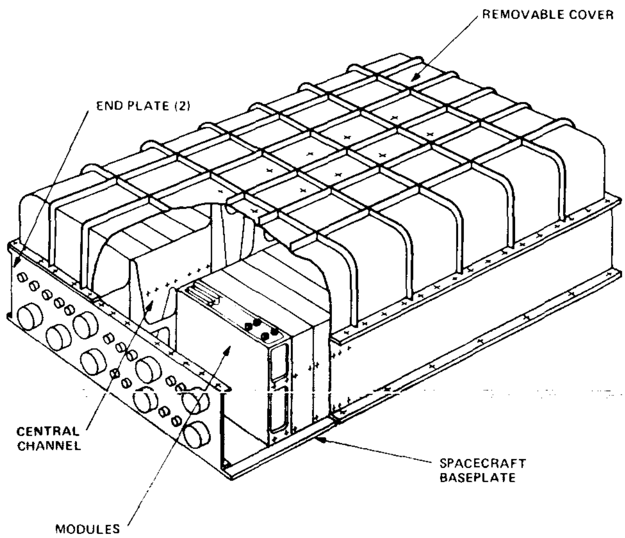


Figure 5. Sensor Subsystem Conceptual External View

The Stable Local Oscillator (STALO) is the heart of the subsystem. It is the source of all clocks and timing pulses used by the subsystem and serves as the input to the frequency synthesizer that produces the S-band carrier. All clocks and timing signals are derived from the STALO by the PRF/Timing unit and distributed to the appropriate units. The STALO frequency (72.27 MHz) is multiplied by 33 in the range dispersion unit, where a biphase code modulates the S-band carrier. The encoded S-band signal (2385 MHz) is gated into the transmitter, where it is amplified to a 350 watt peak power S-band pulse.

There are two transmitter output ports, one to the altimeter antenna, the other to the HGA. When imaging, the output network connects the transmitter output to the HGA during the high-power transmit time and steers the target echo power captured by that antenna to the receiver. During the altimeter function, the output network connects the transmitter altimeter port to the altimeter antenna and directs the echo energy to the receiver.

The receiver amplifies the S-band echo power and provides the radar sensitivity. The echo information is then downconverted to IF and amplified further. A second downconverter in the baseband processor generates signals which are digitized. The resultant digital words are sent to the data formatter unit which rate-buffers the data.

After combining the SAR imaging data with altimetry data, time tags, and format headers, the data formatter provides the data stream, which is clocked across the spacecraft interface in two parallel streams at a 403.2 kbps rate each.

The sensor also collects radiometer samples every burst cycle to obtain passive radiometric measurements of the planet's surface brightness temperature. Within the receiver, a separate integrate-hold-dump circuit is provided for the radiometer samples. Radiometer and calibration measurement samples are interleaved, with one or the other taken every burst. Calibration is normally accomplished by a radiometer measurement of the receiver protect switch. Occasionally, cold-sky observations may be taken. Radiometric measurement data are digitized by a 12-bit A/D converter and sent to the data formatter, where they are included with the radar burst header.

Summary

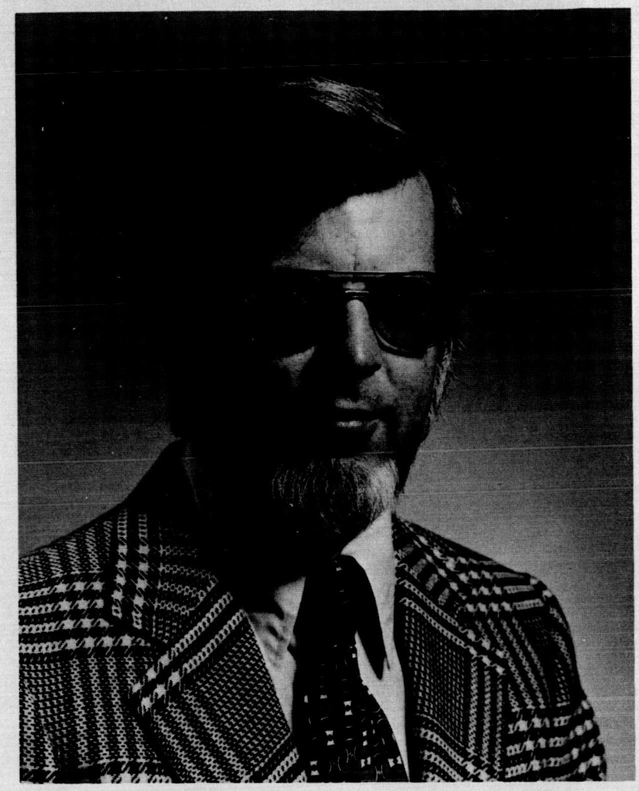
The Magellan mission presents challenging radar design requirements that have been satisfied through the use of an existing Voyager antenna for the SAR function and newly developed sensor and altimeter antenna subsystems. The sensor uses a block adaptive quantizer to maximize science data return with minimum transmission of radar data back to Earth.

Acknowledgement

I wish to thank A. Edgerton of Hughes Aircraft Company for his help with this paper.

The Author

Dr. William T. K. Johnson grew up in various parts of the world as the son of Foreign Service parents. A Bachelor of Science degree in Physics was earned at the University of North Carolina. A Master of Science in Atmospheric Physics and a Ph.D. in Nuclear Physics were obtained from the American University in Washington, D.C.



Bill worked for the Harry Diamond Laboratories in Washington, D.C., and the Rand Corporation in Santa Monica, California. In 1972, he joined the General Research Corporation in McLean, Virginia to work in the area of nuclear vulnerability of anti-ballistic missile systems. At that time, he also met and married Toni Cavanagh. With JPL since 1975, Bill has radar experience that includes work on the SEASAT SAR, and SIR-A. He has been involved with JPL's Venus-related radar missions since 1977, and currently is the Radar System Engineer for Magellan. Bill enjoys tennis, hiking, and keeping his old car running.

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MAGELLAN SAR PROCESSOR DESIGN

8P.

Raymond Piereson
Michael Y. Jin

Introduction

Knowledge of some aspects of the Magellan radar system design is critical to developing an understanding of the associated SAR processing function. The preceding articles contain much of the necessary system design information. This article expands upon some of the radar system design characteristics, which are especially important to the SAR processor design, and describes the Magellan SAR processor design.

Figure 1 presents a diagram that describes the SAR data flow. The SAR data acquired by the sensor are input to the SAR processor along with several types of ancillary data. The SAR processor operates on these data to produce SAR image strips (in digital form) corresponding to each orbit revolution. These image-strip data and associated ancillary data are then used to produce a variety of mosaicked image data products that comprise both digital data tapes and photo products.

For a variety of reasons, reported in the preceding papers, the Magellan SAR data have some unusual characteristics which have a strong effect on the SAR processor design. Some of these characteristics are summarized in Table 1. The variable burst parameters are controlled by periodically updated command sequences. Information regarding observation geometry is available from ancillary data.

Each burst of SAR data provides information regarding the patch of the planet surface that is within the antenna beamwidth at the time of the burst. By performing appropriate SAR processing, one can produce a single-look SAR image of that patch. The burst timing parameters are such that there is a large degree of overlap between successive image patches. By performing an appropriate geometric rectification process on each single-look image, it is possible to register and combine

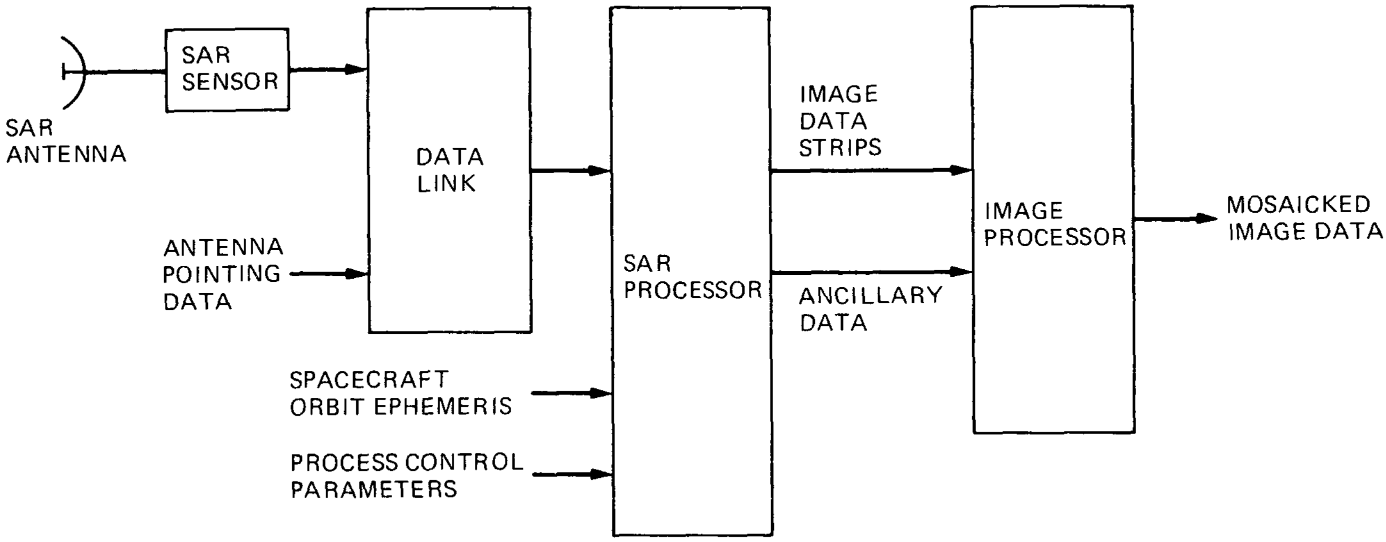


Figure 1. SAR Data Flow Diagram

corresponding pixels. The result is production of a continuous multi-look image strip.

Compensation must be made to individual pixel values to account for parameter variations which affect system gain. Factors treated in this compensation process include the following:

- antenna gain pattern
- sensor-target range
- number of pulses per burst
- receiver gain setting
- telemetered calibration factors

The SAR processor also performs computations to determine the location of pixels in Venus-centered coordinates. This information is used to perform the image mosaicking function in the image processor.

Table 1. Magellan SAR Data Characteristics

TRANSMITTED PULSE

- 60-bit CODE BIPHASE MODULATES CARRIER
- 2.26 MHz CODE CHIP RATE

BURST MODE

- APPROXIMATELY 6,000 BURSTS PER ORBIT
- VARIABLE BURST DURATION
- VARIABLE BURST CYCLE PERIOD
- SAMPLING WINDOWS INTERSPERSED BETWEEN TRANSMITTED PULSES
- VARIABLE PULSE REPETITION FREQUENCY
- VARIABLE SAMPLING WINDOW DELAY
- VARIABLE SAMPLING WINDOW DURATION
- VARIABLE RECEIVER GAIN

$\left.\right\}$ CONSTANT DURING EACH BURST

OBSERVATION GEOMETRY

- NEAR-POLAR ELLIPTICAL ORBIT
- VARIABLE SENSOR ALTITUDE
- VARIABLE TERRAIN ELEVATION
- VARIABLE ANTENNA LOOK-ANGLE

BLOCK ADAPTIVE SIGNAL QUANTIZER

- 2.26 MHz SAMPLING RATE
- COMPLEX SAMPLES (IN-PHASE AND QUADRATURE COMPONENTS)
- QUANTIZER "GAIN" ADAPTS TO OBSERVED SAMPLE VARIANCE WITHIN BLOCKS OF SAMPLES
- THE TELEMETERED QUANTIZER "THRESHOLD" CORRESPONDING TO EACH BLOCK PROVIDES QUANTIZER TRANSFER FUNCTION INFORMATION
- EACH TELEMETERED DATA SAMPLE COMPRISES TWO IN-PHASE BITS AND TWO QUADRATURE BITS

SAR Data Products

During each orbit of the normal mapping phase of the Magellan mission, the radar sensor will acquire SAR data corresponding to a curved strip that has a nominal north-south orientation. The SAR processor will produce digital image data from the SAR data which are telemetered to the Earth. Because of parameter variations during each orbit revolution, the characteristics of the image data will also vary. Some of the characteristics of the image data are as follows:

- image strip length ~ 15,000 km
- image swath width ~ 20-25 km (variable)

- along-track resolution ~ 120 m
- cross-track resolution ~ 110 to 270 m (variable)
- pixel spacing = 75 m

The resolution reported above is for the "full-resolution" rendition of the image data. It is also planned to produce a "compressed" rendition of the image data, which is obtained by averaging 3x3 arrays of full-resolution pixels. The full-resolution image data corresponding to each orbit revolution will be recorded on a separate reel of 6250 bit-per-inch computer-compatible tape (CCT) along with selected ancillary data. (These are called Full-Resolution Basic Image Data Records, or F-BIDRs.) The compressed-resolution imagery corresponding to each set of eight consecutive orbits will be recorded on a separate reel of CCT. (These are referred to as C-BIDRs.) The F-BIDRs and C-BIDRs are delivered to the image processor which combines data from adjacent orbits to produce the following types of mosaicked image data records:

- Full-resolution with 75 m pixel spacing (F-MIDRs)
- Compressed-Once with 225 m pixel spacing (C1-MIDRs)
- Compressed-Twice* with 675 m pixel spacing (C2-MIDRs)
- Compressed-Thrice* with 2025 m pixel spacing (C3-MIDRs)

* Each type of compressed image data is obtained by averaging a 3x3 array of pixels from previous higher-resolution renditions of the data.

The entire imaged surface (except for a small area near the pole) will be covered in each type of compressed MIDR product. A selected 15% of the imaged surface will be covered by the F-MIDR products. Mosaicked image data will be produced both in the form of digital records (on CCT) and in the form of photo products. Various types of enhancement processing will be applied to many of the mosaicked image data products.

SAR Processor Development Context

Digital SAR processing is often a very demanding computation task. Digital processing of SAR data from space missions has been performed on digital computer systems which incorporate up to four array processors to speed up some of the computation tasks. With this approach, it still takes approximately two hours to process 18 seconds of SEASAT SAR data. Because this throughput rate was regarded as inadequate, JPL undertook development of an Advanced Digital SAR Processor (ADSP) with the capability to process SEASAT and SIR-B SAR data at or near the real-time data-acquisition rate. This development is now nearing successful completion.

A block diagram of the ADSP is presented in Figure 2. The ADSP comprises a control computer (VAX-11/730), a variety of specialized data input/output and display equipment, and a custom-designed digital correlator subsystem which incorporates approximately 25,000 integrated circuits.

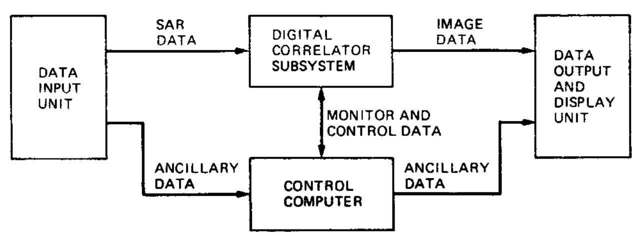


Figure 2. Advanced Digital SAR Processor Block Diagram

During the planning phase of the Magellan mission, it was determined that the best approach to meet the SAR processing requirements would be to augment the ADSP. This augmentation is currently under way and scheduled for completion by 1 October 1988. Preliminary design studies indicate that the Magellan SAR processing function will be performed at more than twice the data-acquisition rate. (SAR data acquired during a 37-minute interval of each orbit will be processed into image data in less than 18 minutes.)

The following sections of this article present more details regarding the Magellan SAR processor design and the associated augmentation of the ADSP. (It is of interest to note that the ADSP is planned to be further augmented to meet the requirements of the SIR-C mission. Thus, the ADSP is being evolved into a multimission SAR processor.)

Magellan SAR Processing Functions

The basic principle of signal processing for the Magellan burst-mode SAR data is very similar to those of certain airborne imaging radars. The processing involves range pulse compression to achieve range resolution and Doppler beam sharpening to achieve azimuth resolution. The latter process is usually realized by a fast Fourier transform (FFT) which acts as a spectrum analyzer to separate the received echo into its Doppler frequency components. The output of such a process is commonly referred to as the range-Doppler bank. In Magellan SAR processing, this represents a partially completed single-look framelet.

Complete processing for a Magellan single-look framelet is more complicated due to the following reasons. First, at large orbit true anomaly angles, the sensor velocity vector has a large radial component which causes a fast rate of change of sensor-target distance. This causes a large Doppler frequency shift in each echo as well as significant target range migration within each burst of pulses. Both of these effects must be compensated for during processing in order to meet stringent image quality requirements. Second, to form a continuous multi-look image strip, each single-look image must be geometrically rectified. This process involves pixel resampling to convert the single-look framelet from the range-Doppler projection into another specified projection. A sinusoidal projection is used at most latitudes, and an along-track/cross-track (AT/CT) projection is used near the pole. Third, in order to accomplish radiometric compensation, a two-dimensional gain compensation function must be generated and multiplied with the image samples of each single-look framelet.

After the single-look framelets have been produced, the following processes are required to form an image strip. First, a framelet truncation is required to suppress samples outside of the prescribed azimuth processing bandwidth (specified by the radar system engineering team) and outside of a specified pair of range boundaries. The purpose of this step is to eliminate pixels which exhibit substandard quality. Then, an overlay process must be performed. Its functions include detection to convert each complex pixel value into its intensity, look summation to accumulate intensity from each look, and intensity normalization of each pixel by its associated number of looks.

The functional block diagram in Figure 3 describes the Magellan SAR signal processing performed in the digital correlator subsystem (DCS). This diagram describes both the SAR data path and the process control parameter path. Note that the DCS performs all of the processing steps described above. Also note that the DCS incorporates capabilities for image display and video recording.

One of the functions of the control computer is to derive a set of DCS control parameters which accommodates the variations of radar parameters and changes of sensor-target geometry from burst to burst. In SEASAT and SIR-B systems, control parameters such as the Doppler centroid and Doppler frequency rate are derived from the radar data using so-called clutterlock and autofocus processes. This approach was necessary for those missions because the available ephemeris and antenna-pointing information were not sufficiently accurate to be the basis for SAR processing control. However, during the preliminary design phase of the Magellan mission, it was determined that the ephemeris and antenna pointing data will be sufficiently accurate to be the basis for both SAR processor control and mosaic process control. Because it enabled a substantial reduction in control process complexity, it was decided to use these data as the normal basis for Magellan SAR

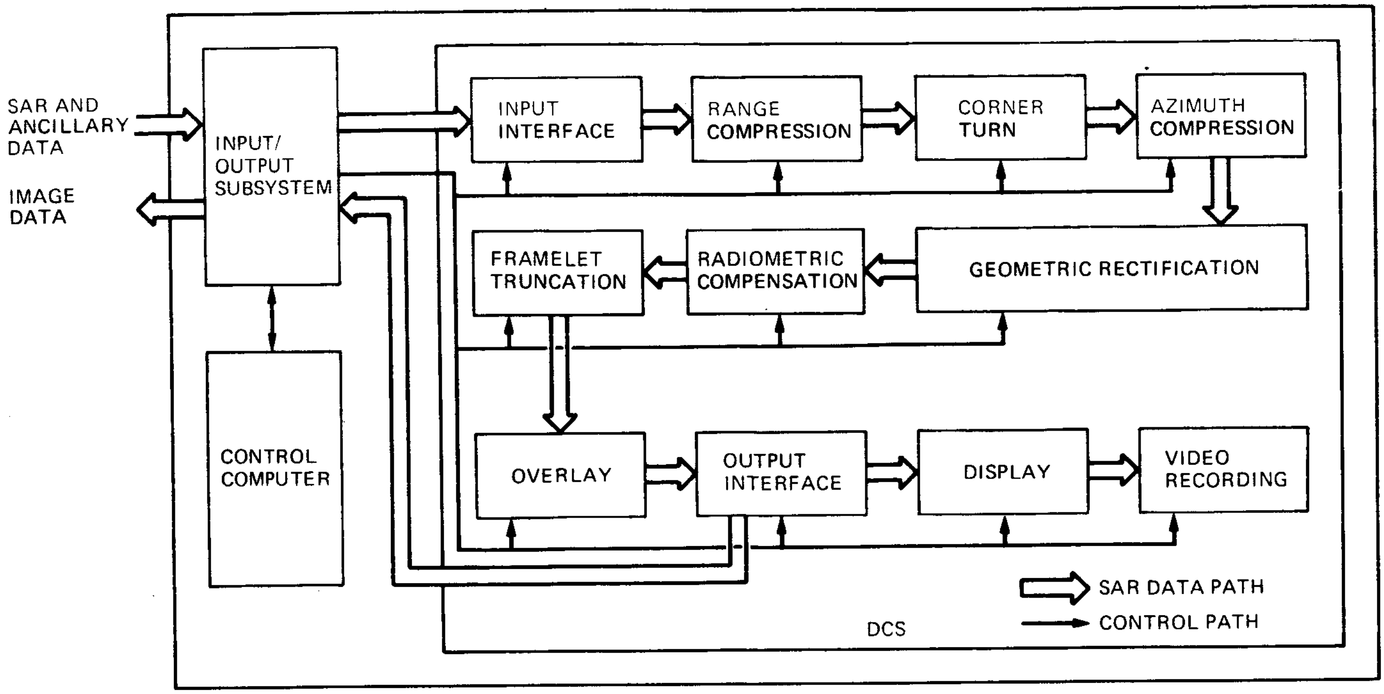


Figure 3. Digital Correlator Subsystem Functional Block Diagram

processing control. Therefore, clutterlock and autofocus processes will not be needed as a routine process; they will be used periodically to check the accuracy of SAR process control parameters obtained from the ephemeris and antenna pointing data.

One of the functions of the input/output subsystem is to perform a Block Adaptive Quantizer (BAQ) sample reconstruction process to convert each two-bit integer into a floating point number based on the information of the threshold value and system gain.

Processing Algorithm Design

This section gives detailed descriptions on the algorithm design of each processing function. These algorithm designs were formulated so as to minimize the required amount of augmentation of the ADSP. A detailed performance analysis showed that this design meets all the processing requirements.

Range pulse compression is performed by a fast Fourier correlation approach which involves a forward FFT, a reference function multiply, and an inverse FFT. A large set of range reference functions is generated in the processor initialization phase and stored in a fast memory. Each range reference is able to compensate for a limited range of Doppler shift and to make a fine-scale range walk compensation. A coarse range walk compensation is made by offsetting the range position of the output samples. A ramp generator is used to provide the range walk function. Its output is split into the integer and fractional parts of range bins to provide control for the coarse- and fine-range walk compensation functions, respectively.

Azimuth compression is accomplished by the following steps. First, a deramp reference prescribed by the control computer is multiplied to the range-compressed burst data along the azimuth direction. This reference is the product of a Kaiser weight and a linear frequency modulated (FM) signal with a small time-bandwidth product. The Kaiser weight is selected for impulse response shaping to suppress side lobes. The linear FM is used to remove the quadratic phase variation of the response. Zeros are appended so that the resultant number of array samples is an integer power of two. Also, a circular shift is performed to place the mid-sample of each burst at the beginning of the array. The final step in the azimuth compression process is to perform a forward FFT.

The geometric rectification process is accomplished by two cascaded one-dimensional resampling processes. When using a sinusoidal projection, the first resampling is to extract samples at the intersections of the iso-latitude lines and iso-Doppler lines by applying interpolation on neighboring range samples. The second resampling is to extract samples at the intersections of the vertical lines of the sinusoidal projection and the iso-latitude lines by applying interpolation on neighboring Doppler samples. Interpolation along each dimension is accomplished through weighted summation of four adjacent samples. The weighting coefficients take the form of a cubic spline function. In the resampling process, the coordinate of the output samples is determined by a second-order polynomial, where all three coefficients of this polynomial vary as functions of a second-order polynomial.

The radiometric gain compensation function is also generated by a quadratic polynomial generator, where all three coefficients of this polynomial vary as functions of a second-order polynomial. The radiometric compensation process is performed on the geometrically rectified samples.

Control Parameter Generation Design

A critical part of the control parameter generation is to locate the boresight intercept point (BIP) on the surface, using a topographic model, including allowance for atmospheric refraction. This process requires tracking the boresight ray path by applying Snell's law on each of a finite number of atmosphere shells which are used to model the atmosphere. To solve for the BIP location on the planet's surface, linear approximation for both the ray path near the surface and the topographic variation shall be used to enhance the efficiency. In the above process, a companion output is the apparent range between the sensor and the BIP. This apparent range is directly related to the boresight echo delay time.

The sensor position and velocity vectors at a specified time can be extracted from the ephemeris data. With the sensor and BIP status vectors known, parameters such as the boresight Doppler frequency and the Doppler frequency rate (to be used in range and azimuth compressions, respectively) are computed directly using well-known equations.

To generate control parameters for the geometric rectification and radiometric compensation processes, it is first necessary to determine the apparent range, antenna look-angle, and the Doppler frequency associated with several points in the vicinity of the BIP. An efficient approach was devised which uses a perturbation method to avoid repeating the ray path finding process.

Processor Architecture Design

Figure 4 gives the detailed architecture design of the Magellan DCS. The range compression module is identical to that used for SEASAT and SIR-B continuous-mode processing. The only difference for Magellan is the content of the range reference buffer. The azimuth compression module requires a minor augmentation to perform the circular shift and to generate a Kaiser-weighted deramp reference function. Another minor augmentation is to provide the capability to generate the radiometric gain compensation function.

The major augmentation is in the multi-look overlay module. In SEASAT and SIR-B continuous-mode processing, overlay is very straightforward since the size of each look and the relative geometry between looks do not vary. In Magellan burst-mode processing, the size and orientation of the framelet boundary both vary from burst to burst. This causes a significant variation of the number of looks from pixel to pixel near strip boundaries. Consequently, a look-index buffer is required to track the number of looks for each pixel. The operations of all the modules, except the augmented multi-look

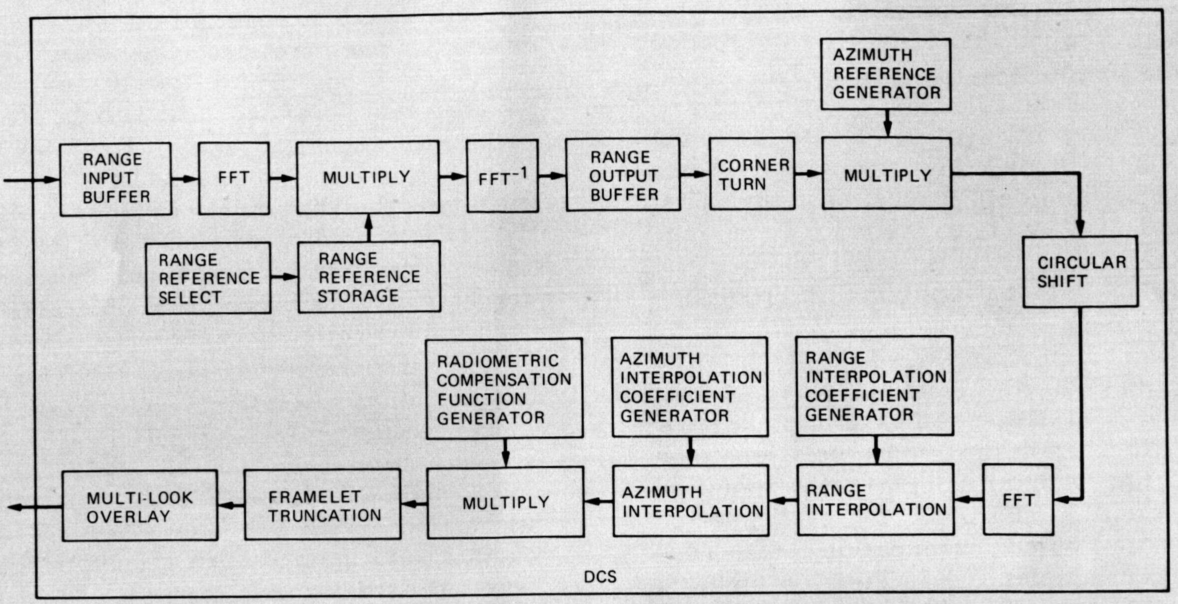


Figure 4. DCS Architecture Design

module, are based on synchronous timing signals.

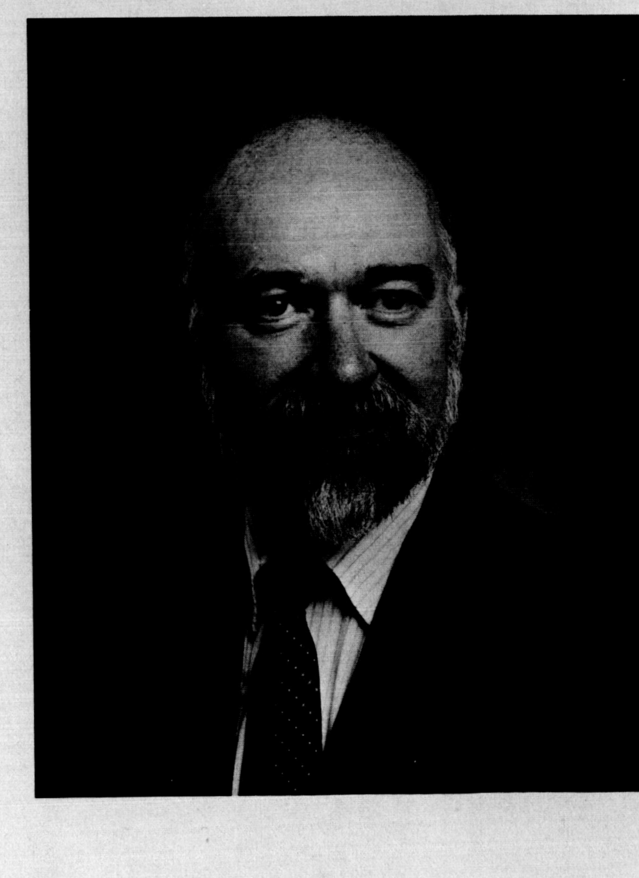
In addition to the augmentations in the DCS, the central computer will be upgraded to a VAX 11/785 to meet the throughput rate requirement of generating the control parameters.

Closing Comments

The Magellan SAR processing requirements present some unusual and interesting design problems. The JPL Advanced Digital SAR Processor (developed under sponsorship from the NASA Office of Aeronautics and Space Technology) provides a valuable foundation upon which to build a SAR processor for Magellan. The Magellan SAR processor system design task was recently completed and the ADSP software and hardware augmentation tasks have begun. Analysis and simulation results indicate that the Magellan SAR processor will meet all specified performance requirements.

The Authors

Raymond Piereson, the Radar Data Processing Engineer for the Magellan Project, supervises the group responsible for the SAR processor system engineering and software development tasks. A member



of JPL's technical staff since 1958, Ray has performed a variety of system engineering and subsystem development tasks in support of the Ranger, Mariner, Voyager, SEASAT, and SIR-B missions. He holds a Bachelor of Science from Michigan State University, and is a member of Tau Beta Pi and Eta Kappa Nu. A bicycle enthusiast, Ray averages 4,000 miles per year.

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